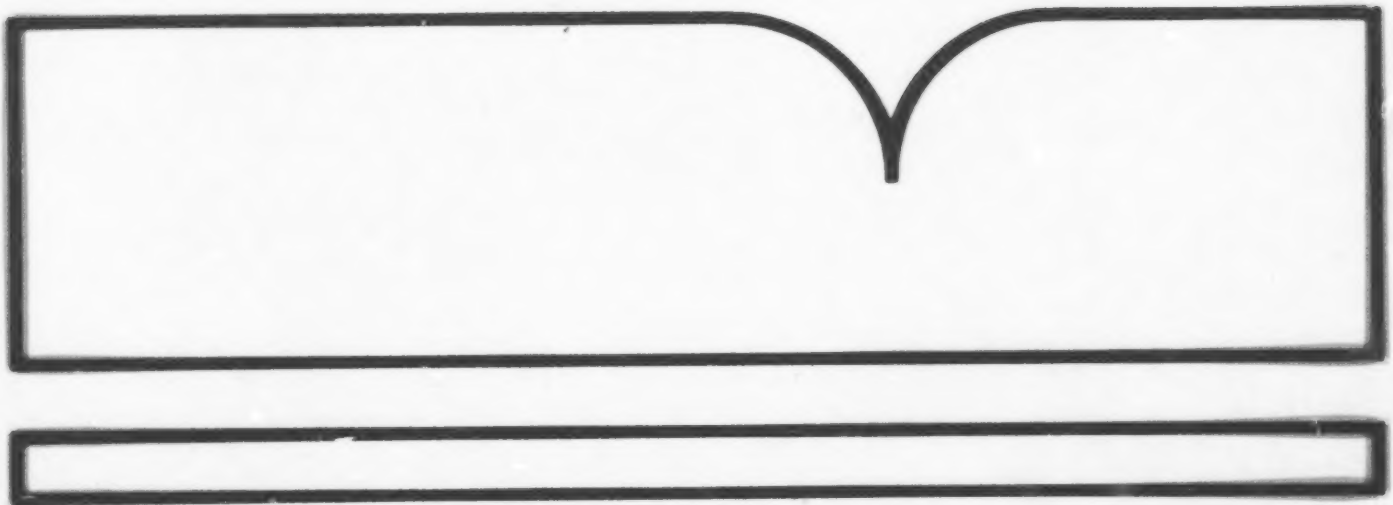


PB86-102324

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Complex Terrain

(U.S.) Environmental Protection Agency
Research Triangle Park, NC

Sep 85



U.S. Department of Commerce
National Technical Information Service

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EPA/600/D-85/200
September 1985

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by

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TECHNICAL REPORT DATA (Please read instructions on the reverse before completing)		
1. REPORT NO. EPA/600/D-85/200	2.	3. RECIPIENT'S ACCESSION NO. PB86 102324/AS
4. TITLE AND SUBTITLE STACK HEIGHTS AND LOCATIONS IN COMPLEX TERRAIN		5. REPORT DATE September 1985
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) R. E. Lawson, Jr. and W. H. Snyder		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Atmospheric Sciences Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711		10. PROGRAM ELEMENT NO. CDTA1D/09 - 3004 (FY-85)
		11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Atmospheric Sciences Research Laboratory - RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED
		14. SPONSORING AGENCY CODE EPA/600/09
15. SUPPLEMENTARY NOTES		
16. ABSTRACT Terrain amplification factors were measured for a variety of source positions (locations and heights) both upstream and downstream of two model hills, an axisymmetric hill and a two-dimensional ridge. The spatial variation of these terrain amplification factors was used to delineate the vertical and longitudinal extent of the areas where excess concentrations (terrain amplification factors greater than 1.0) occurred. For the axisymmetric hill, a region of 40% excess concentration was found to extend a maximum of 1.8 hill heights in the vertical, 14 hill heights upstream, and 10 hill heights downstream. For the two-dimensional ridge, this region of 40% excess concentration extended 2.2 hill heights in the vertical, 8 hill heights upstream, and 15 hill heights downstream. Maximum terrain amplification factors for both the axisymmetric hill and the two-dimensional ridge were found on the downstream side of the hills and had values of approximately 5.6 and 6.8 respectively.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC		19. SECURITY CLASS (This Report) UNCLASSIFIED
		20. SECURITY CLASS (This page) UNCLASSIFIED
		21. NO. OF PAGES 7
		22. PRICE

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STACK HEIGHTS AND LOCATIONS IN COMPLEX TERRAIN

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1. INTRODUCTION

Formulas for determining appropriate stack heights have been established for those cases where a structure in the immediate vicinity of the stack is responsible for inducing downwash (Snyder and Lawson, 1976; Huber, 1981; Lawson and Snyder, 1983). Similar criteria for determination of stack height and location in complex terrain have yet to be developed. This study examines one approach to establishing general guidelines for estimating the effects of sources located near terrain obstacles or, alternatively, for determining an appropriate stack height and location required to avoid excessive ground-level concentrations.

The effect of complex terrain on the transport and diffusion of pollutants from a nearby source is generally to increase ground-level concentrations (glc's). Considering a source upwind of a hill, the maximum glc is increased because the convergence of the streamlines brings the plume centerline closer to the hill surface and the increased turbulence effected by the hill diffuses larger concentrations to the surface (Hunt et al, 1979). For a downwind source, the maximum glc may be increased due to (a) streamlines descending toward the surface in combination with greatly enhanced turbulence and reduced transport speeds, and/or, if flow separation occurs, (b) the plume being recirculated within the cavity on the lee side or being transported directly to the surface (Castro et al, 1982).

If the source is upstream of the hill and the pollutant is emitted at a low level, the maximum glc will occur upstream of the hill, so that the effect of the hill will be negligible. If the source is tall enough, the maximum glc can occur far downstream of the hill, so that, again, the effect of the hill will be negligible. If the source is far enough upstream that the plume widths (σ_y and σ_z) are comparable to or larger than the hill dimensions, the effect of the hill will again be negligible. Hence, a region or "window" (Hunt et al, 1979) exists such that pollutants emitted within that window result in "excessive" ground-level concentrations.

Recent fluid modeling studies (Snyder, 1983; Castro et al, 1982; Khurshudyan et al, 1981) have indicated that large increases in concentration (factors as large as 15) can result from placement of sources near terrain, but systematic stu-

dies to establish values and "windows" of excess concentration have not been done. The purpose of this study was to establish values and "windows" of "excessive" concentrations for typical hill shapes that might be found in the real world. Two hill shapes were chosen to represent what were believed to be two relative extremes of realistic hill shapes. The model hills, one axisymmetric and the other two-dimensional, represent idealizations of typical hills in shape and slope, so that the results of the study should be rather broadly applicable.

The results are presented in terms of terrain amplification factors (TAF's), defined as the ratios of the maximum glc's in the presence of the hills to the maximum glc's in the absence of the hills (in flat terrain). Note that this definition does not involve the location of the maximum glc's; the maxima will generally occur at very different distances downstream from the source in the two situations (with and without terrain), but it is the values of the maxima which are being compared, wherever they occur. Note also that the "excess concentration" is easily obtained from the TAF; they differ by the additive factor of unity, i.e., a 40% excess concentration, for example, is represented by a TAF of 1.4.

The "window" concept allows the specification of a region or area (say, in a vertical plane) such that sources placed inside the area would result in TAF's exceeding some specified value. Once an acceptable excess concentration or TAF is decided upon, it is a simple matter to trace the window on the TAF contour map as the area to be avoided. Conversely, from such maps, the likely maximum glc for a potential site and stack height can be estimated. The use of terrain amplification factors simplifies the application of these data to full-scale situations. The expected maximum ground-level concentration in the absence of the obstacle is calculated (from mathematical models or standard curves), then the concentration in the presence of the obstacle is simply the product of this quantity and the TAF.

2. EXPERIMENTAL PROCEDURES AND INSTRUMENTS

2.1 Wind Tunnel

The experiments performed in this study were conducted in the wind tunnel of the U.S. Environmental Protection Agency's Fluid Modeling Facility. Detailed features and operational characteristics of the wind tunnel are described by Snyder (1979).

The technique of Counihan (1969) was used to produce a thick simulated atmospheric boundary

*On assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

layer in the wind tunnel. A combination of castellated fence, elliptic-wedge vortex generators, and surface roughness elements produced a 1 m deep, near-equilibrium boundary layer.

2.2 Models

The axisymmetric hill was an idealized version of Cinder Cone Butte (Lavery et al, 1982), an isolated, nearly axisymmetric hill located in southwestern Idaho. The model was 155 mm high, 1550 mm in diameter, and had the shape of a fourth-order polynomial. The top of the model hill was a relatively flat plateau about 400 mm in diameter, while the sides sloped gradually to the surface with no discontinuities. The maximum slope was 24° .

The two-dimensional ridge was nearly identical in shape and construction to "Hill 5" as described by Khurshudyan et al (1981). The height of the model was 118 mm, its chord was 1180 mm, and its maximum slope was 16° .

Cross-sections of both models can be seen in later figures. Both model hills were coated with fine gravel so as to blend smoothly into the surface roughness panels and to maintain an aerodynamically rough surface.

2.3 Velocity Measurements

Measurements of mean velocity, longitudinal and vertical components of turbulence intensity, and Reynolds stress were made using hot-wire anemometers. A minicomputer system was used to digitize the anemometer outputs, convert the digitized voltages to velocities, and compute flow statistics.

Supplementary measurements were carried out on the downstream side of the axisymmetric hill using a dual Pitot tube to determine the size of the separated wake and locations of the separation and reattachment points.

2.4 Concentration Measurements

A hydrocarbon tracer technique was used to measure ground-level concentrations downwind of the source. The source was ethane, which has a molecular weight very near that of air, so that the plume was neutrally buoyant. The tracer was released through a hollow, perforated plastic ball 10 mm in diameter. This type of source allows for injection of a suitable quantity of tracer gas while at the same time minimizes the effluent momentum in any preferred direction; it simulates a point source and avoids any plume rise. Samples were withdrawn through sampling ports mounted on the surface of the model and on the tunnel floor. The samples were routed to flame ionization detectors (FIDs) which produced an output voltage linearly related to concentration. The output voltage from the FIDs was also sampled by the minicomputer system which computed mean concentrations.

3. BOUNDARY LAYER CHARACTERIZATION

The boundary-layer structure was characterized in terms of velocity, turbulence structure, and dispersive ability. This characterization was carried out in the absence of any model and at the same freestream wind speed as used with the models (4 m/s).

3.1 Velocity

Figure 1 shows measurements of mean velocity and turbulence intensity taken at 6, 10, and 15 m downstream from the start of the roughness panels. Very little change in the structure of the boundary layer occurred beyond 6 m. The model hills were located at 6.5 m (and later at 9.1 m); hence, the effect of changes in the boundary-layer structure are expected to be negligible.

A roughness length of approximately 0.1 mm (~ 10 cm full scale) and $u^*/U \sim 0.04$ were obtained fitting the lower portion of the mean velocity profile to a log-law form.

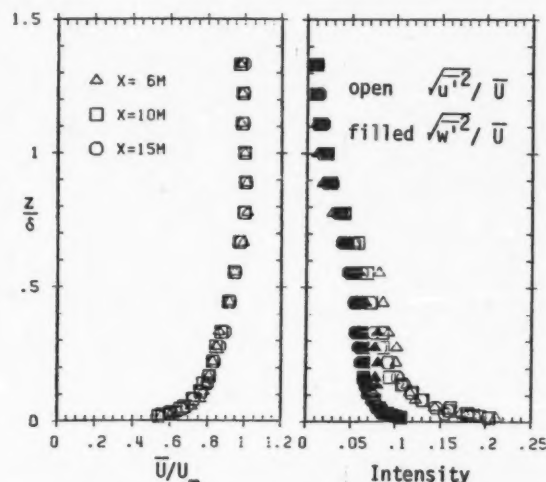


Figure 1. Mean velocity and turbulence intensity profiles in the simulated atmospheric boundary layer.

3.2 Concentration

Tracer concentration was measured as a function of distance downstream of the source for several different source heights. These profiles served as the flat terrain or reference data for later evaluation of terrain amplification factors.

A comparison was made between measured dispersion characteristics in the wind tunnel and dispersion characteristics estimated using Pasquill-Gifford stability categories C and D (Turner, 1970). A scale factor of 1:1250 was used. Near the source, the dispersion was most closely approximated by stability class C, while farther downstream the dispersion was more typical of stability category D.

4. FLOW VISUALIZATION

Some flow visualization experiments were conducted with each hill prior to making quantitative concentration measurements. These qualitative evaluations of the dispersion near the hills were used as a guide in selecting appropriate locations for the tracer source, and in determining whether the flow was separating on the downstream side. Separation was observed for the axisymmetric hill, but no clearly defined recirculating zone was seen downstream of the two-dimensional ridge.

5. RESULTS

In Figure 2, terrain amplification factors are plotted and contoured for both hills. TAFs upstream

of the axisymmetric hill were obtained from a previous study by Thompson and Snyder (1984). Experimental conditions were nearly identical to those used in the current study and the data appear to be consistent with the current results. For both hills, the greatest TAFs occurred with the source on the downstream side; maximum values of 5.6 were observed for the axisymmetric hill and 6.8 for the two-dimensional ridge. With the source on the upstream side, the axisymmetric hill exhibited somewhat higher TAFs than did the ridge; the peak values were 3.6 and 1.8 respectively. The most dramatic difference between the two distributions is the vertical and longitudinal extent of the windows of 40% excess concentration (TAF of 1.4). For the axisymmetric hill, this region extended about 14 hill heights upstream, 10 hill heights downstream, and 1.8 hill heights in the vertical. For the two-dimensional ridge, this same region extended to about 8 hill heights upstream, 15 hill heights downstream, and 2.2 hill heights in the vertical.

In Figure 3, the location of the maximum ground-level concentration has been plotted in terms of distance from the center of the hills. In each case there are three distinct regions: 1) a region near the upstream surface where a plume released from the source will result in a maximum ground-level concentration upstream of the hill, 2) a region upstream of the hill and above the surface where the plume will essentially graze the top of the hill and result in a maximum glc on the hill top, and 3) all other source locations, where the plume goes over the hill and results in a maximum ground-level concentration on the downstream side.

6. SUMMARY AND DISCUSSION

These experiments have shown that, even for sources located significant distances from terrain obstacles (10-15 hill heights), significant increases in maximum ground-level concentration can occur over and above that which would occur in the absence of the obstacle. Using the same scale factor as used for the comparison with Pasquill-Gifford dispersion curves (1:1250) for example, the axisymmetric hill would scale to about 200 m and the ridge would scale to about 150 m. These terrain obstacles would then produce significant excess concentrations for sources located 2.0 to 2.5 km downstream.

Some caveats should be noted before attempting to apply this information directly to real-world situations. In the wind tunnel, the approach wind direction remains absolutely steady. This is seldom the case in the atmosphere where lateral fluctuations in wind direction or "meandering" are more common than not. Such lateral fluctuations tend to spread a diffusing plume laterally, hence lowering the average concentration at any particular downstream location. These lateral fluctuations are frequently enhanced by terrain features so that, by comparison, the wind tunnel results are expected to produce somewhat of an overestimate of the peak concentrations. On the other hand, the hills considered in this study were selected to be representative of a broad range of hill shapes. For hills with greater slope (Castro et al, 1982; Khurshudyan et al, 1981) or more salient edges (Huber, 1976), upstream vortices and lee-side separation may be induced or greatly enhanced. Both phenomena tend to bring plumes closer to the ground, hence increasing maximum ground-level

concentrations. In such cases, the wind tunnel results may prove to be slightly underestimated.

Comparison of the present results with other wind tunnel studies is informative. Snyder and Lawson (1985), in a study of good-engineering-practice (GEP) stack height in complex terrain, applied the results of the current study to determination of appropriate stack height for a power plant. The plant was located some 600 m downwind of a 190 m high, nearly three-dimensional, hill. The current study indicated that the required stack height based on 40% excess concentration (TAF of 1.4) would be about 1.7 times the hill height, or 325 m. A rather laborious evaluation of GEP stack height for the specific terrain arrived at a value of 326 m. The nearly perfect agreement is certainly fortuitous, but it does indicate that studies of such "generic" terrain features can provide suitable guidance for initial estimates of appropriate stack heights and locations in complex terrain.

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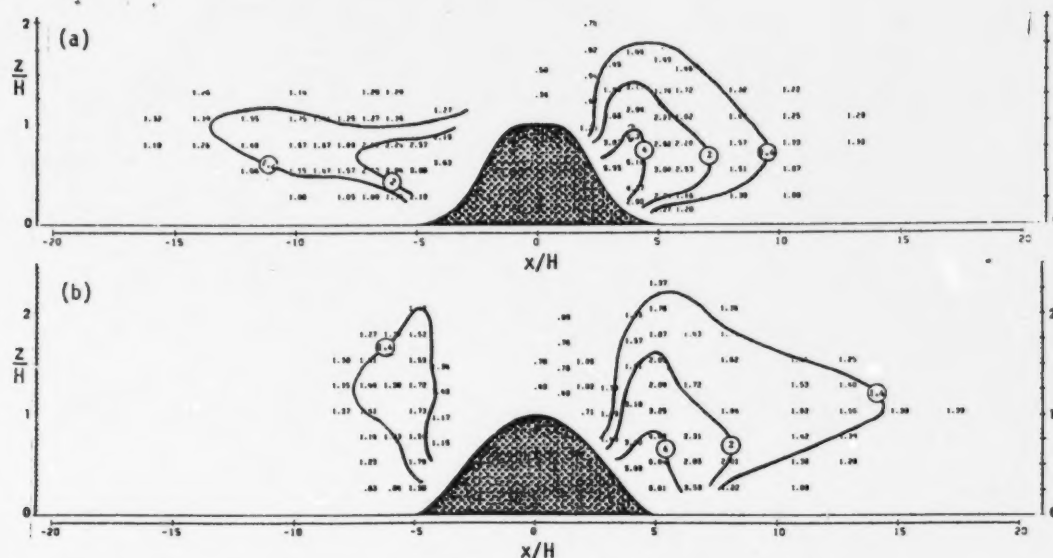


Figure 2. Terrain amplification factors upstream and downstream of (a) the axisymmetric hill and (b) the two-dimensional ridge. Note exaggeration of vertical scale.

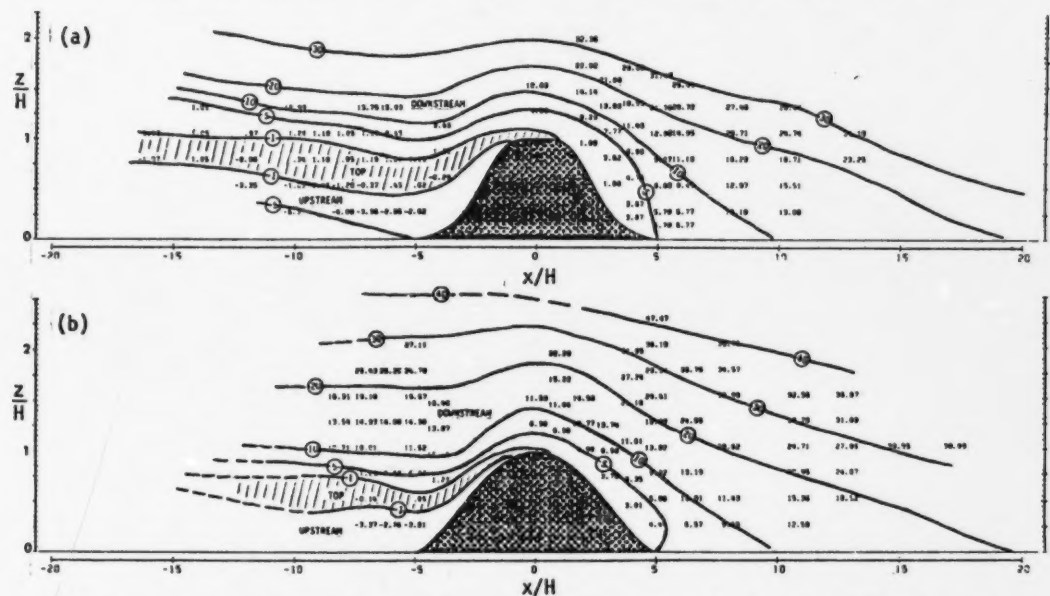


Figure 3. Distances in hill heights from the center of the hill to the location of maximum ground-level concentration as a function of source height and location.

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